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Morphologies of strontium-modified A357 alloy and its mechanisms①

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Abstract: The microstructure evolution for A357 alloy modified by original Al-10Sr alloy was systematically investigated. The results show that the eutectic silicon phase gets finer and more homogeneous with the increase of Sr content and the modifying temperature. Modification at the performing temperature of 740 ℃ and with Sr contents of 0.03% - 0.05% (mass fraction) turns the microstructure into the finest fibers. And the mechanism of evolution was also investigated based on the TEM observation.

Key words: A357 alloy; original alloy; modification; eutectic silicon
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1 INTRODUCTION

The Al-Si system is a simple eutectic, in which the aluminum phase is non-faceted and hypoeutectic alloys are faceted. The minor silicon phase in binary alloys exhibits typically as faceted flake, which seriously deteriorates the mechanical properties by separating the matrix[1]. Fortunately, the flaky Si phase can be modified by several ways: 1) rapid solidification[2]; 2) addition of modifiers, such as sodium, alkaline-earth metals (Sr, Ca, Ba) and selected rare-earth metals (La, Ce, Pr, Eu and Yb)[3, 4]. In the later case, the eutectic flaky silicon is modified to branched fibers with high twin densities, and the primary Si phase flakes assume more nearly spherical shapes, also highly twined[5, 6]. The sodium is one of the most effective modifiers, but sodium in excess of about 0.015% will cause overmodification bands at which the duplex eutectic front is briefly arrested and overgrowth by a film of aluminum[1, 7]. However, the Al-Si alloy modified by strontium has many advantages, such as high mechanical properties and high melt fluidity. A357 alloy is a promising candidate for the materials used in aviation industry[8, 9]. In order to improve its properties the modification process is necessary. The present study aims at investigating the influence of modifying parameters on the microstructure of A357 alloy, such as the Sr content, the modifying temperature. The modification mechanism of strontium on silicon morphology is also given.

2 EXPERIMENTAL

The original Al-Si alloy with the composition listed in Table 1 was melted with an electron resistance crucible furnace to predetermined temperature and held for 30 min for homogenization under argon atmosphere. Then the melt was refined by Al-5Ti-1B alloy at the same temperature. And then, an Al-10Sr modified melt was added into the melt under different processing parameters as listed in Table 2. After that, the modified melt was cast into a resin sand mould with the dimension of d12 mm × 100 mm. The microstructure samples were cut from the casting and observed by SEM and TEM.

Table 1 Composition of original Al-Si alloy (A357) (mass fraction, %)

Si	Mg	Be	Ti	Fe	Others	Al
6.5	0.6	0.07	0.4	< 0.15	< 0.15	Bal.

Table 2 Parameters of modifying process

Mass fraction of Sr/ %	Modifying temperature/ ℃	Holding time/ min
0.01	700	20
0.03	720	40
0.05	740	60
0.07	760	

The SEM observations were performed with an S-570 scanning electron microscope operated at 20 kV. The foils for TEM observation were produced by ion milling using argon ion after mechanical polishing to 30 μm and the samples were examined by a Philips TEM 420 analytical electron microscope operated at 120 kV. During the preparation process of thin films, the silicon and aluminum phases were reduced to equal thickness so that the as-solidified microstructure can be examined by TEM.

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3 EVOLUTION OF MORPHOLOGY MICROSTRUCTURE DURING MODIFICATION PROCESS

The morphology of silicon fibers in unmodified A357 alloy is shown in Fig. 1, which exhibits the shape of needles with the dimensions of about 40 μm in length and 5 μm in width. Some flaky branches can also be observed on the needles. The morphology evolution of eutectic silicon with different Sr content at modifying temperature of 740 ℃ is shown in Fig. 2. When the Sr content is 0.01%, the morphology of Si is changed from needle shape (without modification) to fine dendrite. But the distribution of size is heterogeneous, which varies from 5 μm to 40 μm. However, the heterogeneity of morphology microstructure accompanying the fining of silicon fibers is improved by degrees with the increase of Sr content, as shown in Figs. 2 (b), (c) and (d).

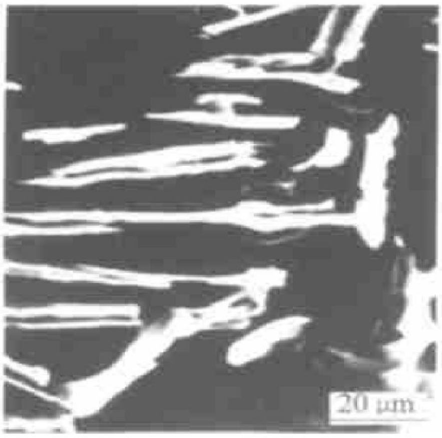

Fig. 1 Morphology of eutectic silicon of unmodified A357 alloy

The evolution process of morphology of the silicon fibers in A357 alloy modified with Sr content of 0.03% under different performing temperatures is shown in Fig. 3. When the performing temperature is low (700 ℃), block or flack with big dimension eutectic silicon can be observed while the content of silicon fibers is low and the silicon fibers are also coarse. But with increasing performing temperature, the proportion of silicon fibers increases and the microstructure gets more homogeneous. Modification at the performing temperature of 740 ℃ turns the microstructure into fine fibers. However, the morphology of silicon fibers does not change obviously with the further increase of temperature, as shown in Fig. 3(c) and (d).

4 DISCUSSION OF MODIFIED MECHANISM

The above observations confirm that the morphology and the mean grain size of eutectic silicon are significantly influenced by the parameters of modification process. The crystal structure of silicon is face centered cubic, in which the plane (111) is smooth while the plane (110) and (100) are coarse. From the view of foundry, the coarse plane will grow more fast than the smooth one. As the result, the morphology of eutectic silicon should be mainly dependent on the growth characteristic of smooth plane, i. e. plane (111) for eutectic silicon in this case. Several studies have attested that the eutectic silicon crystal will grow in the way of twin-plane re-entrant edge (TPRE) growth mechanism [10, 11]. Only one single (111) twin system operates in any one silicon flake segment, although four (111) planes are available.

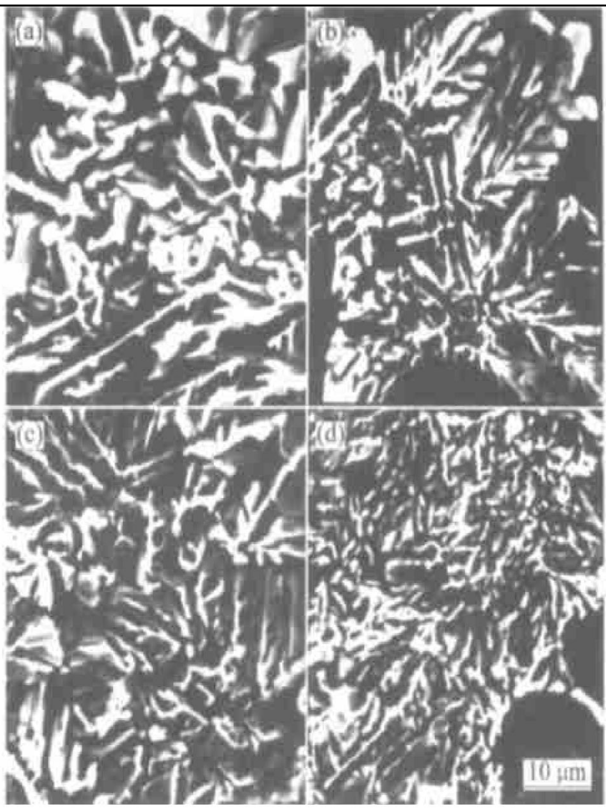

Fig. 2 Morphologies of eutectic silicon with different Sr contents
(a) —0.01%; (b) —0.03%; (c) —0.05%; (d) —0.07%

These observations can be explained by the enormous increase in the twin density of eutectic silicon due to the addition of strontium modifier in relation to theories of modification[4-6]. A logical reason for the increased twin density is that the strontium is absorbed on {111} surfaces of the silicon and lowers down the {111} twin boundary energy. The closer values strongly suggest that strontium might have strong affinity to silicon crystal at the solidification temperature. Several studies have also shown that the element Sr can be attracted on the planes (111) of eutectic silicon and reduce the surface tension of the alloy[12]. Fig. 4 shows the TEM observations of microstructure characteristic

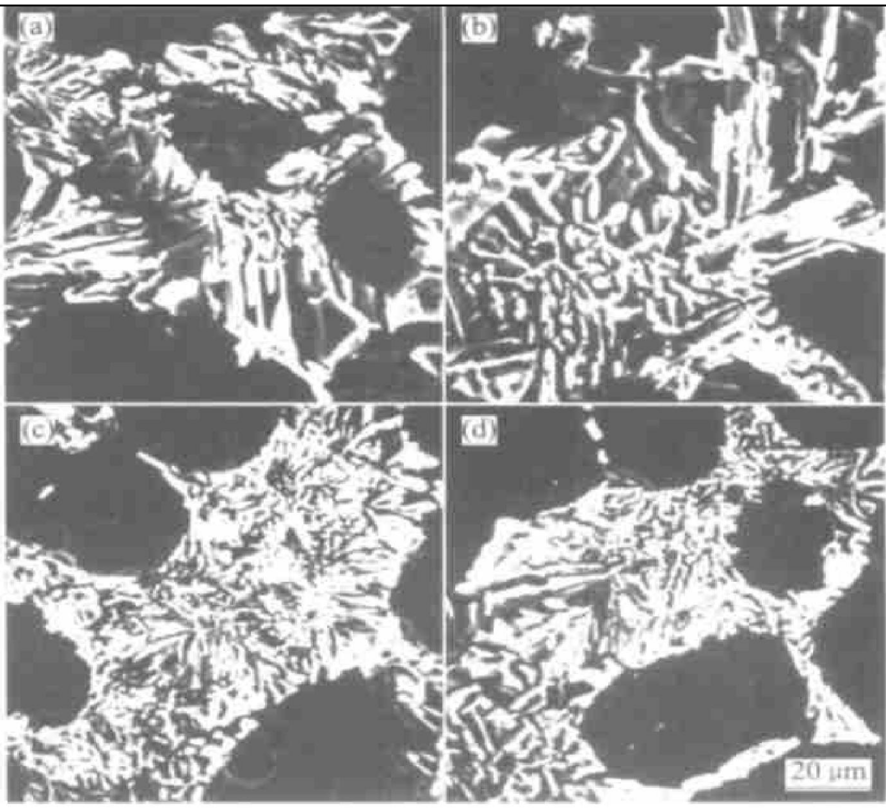

Fig. 3 Influence of performing temperature on eutectic silicon of A357 alloy (0.03% Sr)
(a) —700 ℃; (b) —720 ℃; (c) —740 ℃; (d) —760 ℃

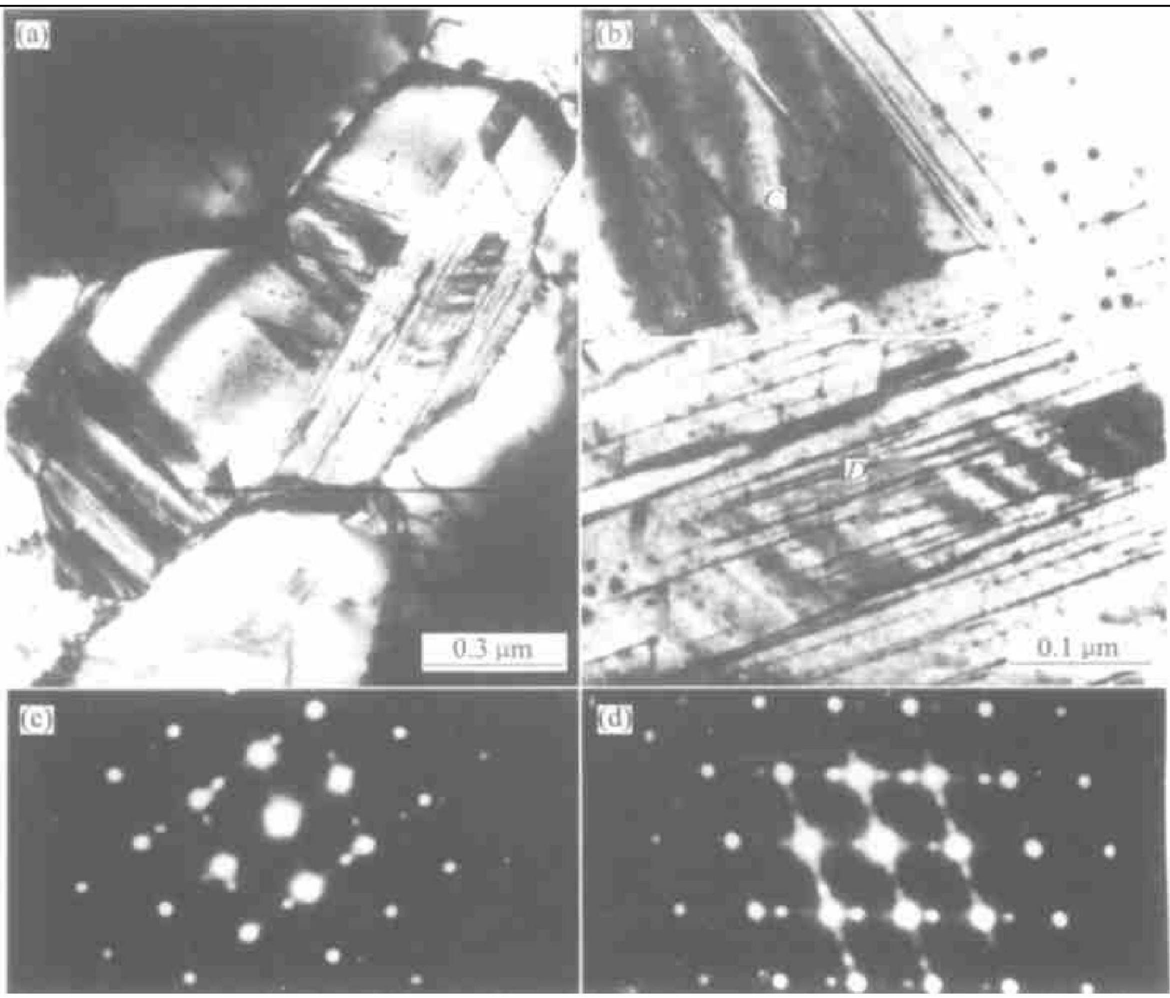

Fig. 4 Twinning characterisitic of eutectic silicon with Sr modification
(a) —Morphology of typical eutectic silicon; (b) —Magnification of (a);
(c), (d) —Diffraction patterns of sites *C*, *D* in (b)

of eutectic silicon modified by Sr. Fig. 4 (a) shows the morphology of typical eutectic silicon and Fig. 4 (b) is its high magnification microstructure. Figs. 4(c) and (d) show the diffraction patterns of sites indicated as C, D in Fig. 4(b). TEM observations show that the operation of (111) twins is responsible for the behavior of Sr modification effects to eutectic silicon.

The redistribution of Sr solute on the crystal planes of eutectic silicon, especially the content on planes {111} will cause two results: one is that the segment of Sr will embed in eutectic silicon and induce twin; the other is that element Sr accumulated on the solidification interface of solid and liquid will result in composition undercooling. Based on the composition undercooling theory, the undercooling temperature ΔT is determined by

$$\Delta T = M_1 c_0(1 - K_0)[1 - \exp(-vx/D_1)]/K_0 \tag{1}$$

where M_1 is the slope of liquid line, c_0 is the content of Sr, x is the distance to the interface between solid and liquid, v is the solute transmitting velocity.

From Eqn. (1), it is concluded that ΔT will increase with the increasing of Sr content. And the increase of ΔT will promote the growth of eutectic silicon by the way of dendritic growth. Therefore the morphology of eutectic silicon gets finer with the increase of Sr content. The increase of modifying temperature will cause increase of the transmitting velocity, v, then the undercooling temperature ΔT. So the modifying temperature has similar effect on the Sr content. However, with further increasing mordifying temperature, the transmitting velocity of solute will attain limited value, then significantly soften its effect.

5 CONCLUSIONS

1) The morphology of eutectic silicon is seriously influenced by the content of Sr and modifying temperature. Eutectic silicon gets finer and more homogeneous with the increase of content of Sr and modifying temperature. Modification at the performing temperature of 740 ℃ and with Sr contents of 0.03%－0.05% turns the microstructure into the finest fibers.

2) The operation of (111) twins is responsible for the behavior of Sr modification effects on eutectic silicon.

3) The undercooling temperature ΔT is the function of the content of Sr. The increase of content of Sr and performing temperature will increase ΔT, therefore promote the fining behavior of silicon.

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